FINAL REPORT
Modeling of Habitat and Foraging Behavior of Beaked Whales in the Southern California Bight

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LONG-TERM GOALS

The overall goal of this project was to improve our understanding of beaked whale distribution and foraging behavior and to describe inter-specific differences. We investigated spatio-temporal patterns for Cuvier's beaked whale and a beaked whale producing echolocation signal type BW43 in the Southern California Bight using passive acoustic encounters, comparing data gathered from line transect surveys and autonomous recorders.

OBJECTIVES

The objective of this project is to improve our understanding of beaked whale distribution and foraging behavior and to describe inter-specific differences. Knowledge about foraging behavior and habitat preference and potential shifts due to seasonal or oceanographic factors are crucial for mitigation of impact during naval operations and for population management. Understanding habitat preference of

poorly known species, such as beaked whales, can lead to their visual identification during fieldwork and improved understanding of foraging behavior and habitat preference.

APPROACH

High-Frequency Acoustic Recording Packages (HARPs, Wiggins & Hildebrand 2007) have collected acoustic data at 18 sites within the Southern California Bight (SCB) since 2006. Sites ranged from 200 to 1400 m of depth and were covering a broad range of habitats. Acoustic signal processing for HARP data was performed using the MATLAB (Mathworks, Natick, MA) based custom program Triton (Wiggins & Hildebrand 2007) and other MATLAB custom routines. Data were screened manually and with automated detectors. We compared acoustic encounters of beaked whales with ten different beaked whale type signals known for the North Pacific (Baumann-Pickering et al. 2013) to determine a species label.

Data from acoustic line-transect surveys (2008-2011) carried out by NOAA Southwest Fisheries Science Center (Jay Barlow) in collaboration with Bio-Waves, Inc. (Tina Yack), supplied the second beaked whale data set for the habitat modeling effort. These data were post-processed using PAMGuard Software to verify beaked whale encounters and assign final species identifications to acoustic encounters when possible and when no associated visual encounter occurred (Figure 1).

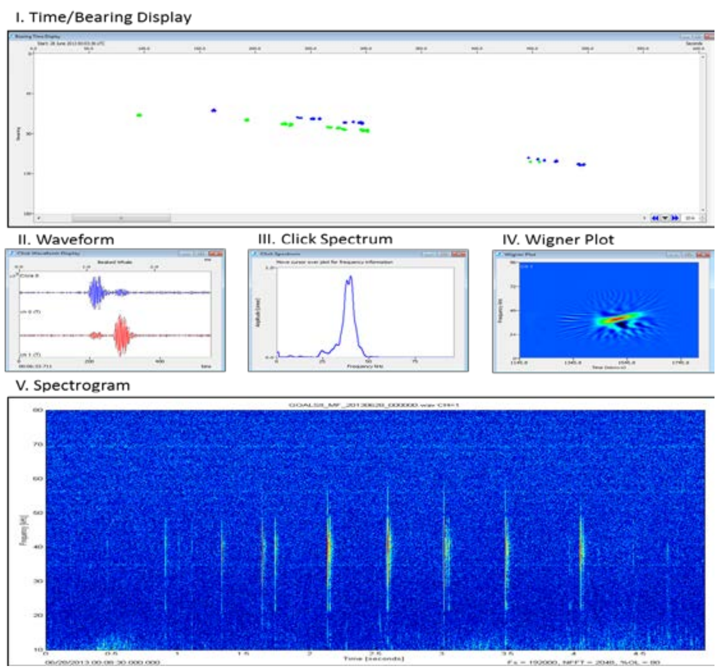

Figure 1. PAMGuard semi-automated species classification of towed array beaked whale encounters. Panel (I) shows echolocation signals detected for the encounter and marked as events with calculated bearing on the y-axis and time along the x-axis (2 individuals are marked in green and blue, respectively). Panel (II) shows the waveform of the selected echolocation signal with amplitude displayed along the y-axis and sample bins (e.g. time) displayed on the x-axis. Panel (III) shows the spectrum display with amplitude on the y-axis and frequency (kHz) along the x-axis. Panel (IV) shows a Wigner plot of the selected echolocation signal. Panel (V) displays the spectrogram of the encounter event with time (seconds) along the x-axis and frequency kHz) along the y-axis (Triton software).

Foraging bouts (buzzes) were automatically detected by an algorithm that searched for consecutive low inter-click intervals (5-10 ms) and low received levels (~20dB lower than prior frequency modulated (FM) pulses during search and approach phase) (Madsen et al. 2005, Johnson et al. 2006, Baumann-Pickering et al. 2010).

Propagation modeling was executed to understand possible differences in detection range of beaked whale signals at the stationary HARP sites. For this purpose we took advantage of the Effects of Sound on Marine Environment (ESME) 2012 Workbench framework (D. Mountain, Boston University; http://esme.bu.edu). Sound propagation models were developed using the Bellhop model.

The manual and automatic detection time stamps of HARP data were stored with the remainder of metadata (e.g. project name, instrument location, detection settings, detection effort) in the metadata database Tethys. The database was used to retrieve physical and biological oceanographic data for habitat model development from outside sources via the ERDDAP interface (Environmental Research Division's Data Access Program, NOAA, Southwest Fisheries Science Center, http://coastwatch.pfeg.noaa.gov/erddap/index.html). The Tethys workbench project was developed under a grant issued through the National Oceanographic Partnership Program (NOPP) to Marie Roch (PI), San Diego State University, with Baumann-Pickering, Hildebrand et al. as co-PIs. We were able to substantially benefit from advances made under the NOPP grant in the management, retrieval, and manipulation of metadata and its mediator capabilities.

Generalized linear mixed models (GLMMs) were used to evaluate the influence of potential predictors of Cuvier's beaked whale occurrence near the different HARPS. The observational unit for analysis was $DPUE_{ikt}$ (detections per unit effort), where i references an 8-day period within the calendar year t, k references a HARP location, and $DPUE_{ikt}$ is an index for the number of minutes with Cuvier's beaked whale acoustic encounters divided by the fraction of time within the 8-day period that the HARP was actually recording (on effort). The index numerator was calculated as 60 times the number of 1-minute periods during which at least one minute with Cuvier's beaked whale FM pulses was recorded. Recording time (index denominator) varied with the number of days of HARP operation (e.g., a HARP might be deployed or retrieved in the middle of an 8-day period) and with duty cycle (HARPs recorded from 25% to 100% of the time while deployed).

WORK COMPLETED

A multi-step automatic detection routine was run on all HARP data collected between 2006 and 2013 in the SCB, capable of detecting FM pulses from Blainville's, Cuvier's, Stejneger's, and Deraniyagala's beaked whale as well as four signal types of unknown origin (BW40, BW43, BW70, BWC), described in Baumann-Pickering et al. (2013), with approximately 5% missed detection rate, varying slightly with changes in ambient sound, species composition, and site-specific animal density. Automatic detection for Baird's and Longman's beaked whales has not been successful with the current automated routine. This resulted in detections from long-term data at 18 sites, a sum of approximately 28 years of recordings in the SCB. Manual inspection of all automatic detections was performed with the help of a machine-assisted classification tool (Baumann-Pickering et al. 2013) to label acoustic encounters to species-level and eliminate false detections.

The towed array data 2008, 2010, and 2011 were post-processed and final quantifications of beaked whale encounters were obtained for the datasets. Using a custom routine in R software, the towed array

trackline effort was divided into 5 km segments for association with static and dynamic oceanographic variables.

Static oceanographic variables (depth, slope, aspect, and distance to the 1000 and 2000 m isobath) were associated with the HARP deployments and the line-transect segments using ARCGIS 10.1 tools. Propagation modeling using the ESME workbench (Bellhop ray-tracing algorithm) was achieved for all HARP sites to determine a scaling factor for detections based on the area over which detections were collected. Dynamic oceanographic variables (satellite measures: sea surface temperature, sea surface height, sea surface chlorophyll *a*, primary productivity; buoy measures: wind direction and speed, wave direction and speed) were queried through the Tethys workbench from the NOAA ERDDAP service for 8-day averages and these variables were then associated with the HARP and towed array survey points. Mean and standard deviation of these variables were calculated over a polygon at the HARP based on the modeled detection area and over an 8 km square centered on each line-transect segment midway position.

A foraging buzz detector was developed and run over time periods when beaked whales were present. False detections were eliminated.

Temporal and spatial patterns of beaked whale presence were explored for Cuvier's beaked whales and the signal type BW43. GLMMs were computed using function lmer from libraries lmer4 and lmerTest in program R version 3.1.1. Estimation was performed using restricted maximum likelihood (REML). We assumed a Gaussian error structure on the response variable $\log(DPUE_{ikt} + 1)$. Variance was inversely weighted by effort (fraction of time recording in *ikt*), so that parameter estimation was more strongly influenced by observations with greater effort. Year (t) and location (i) were treated as random effects. We considered the following static fixed effects associated with each HARP location: depth (in meters); distance (in meters) from the 1000 m and 2000 m isobaths; aspect (degrees); slope (degrees); latitude, longitude and their interaction (in decimal degrees). Additionally, we considered a fixed seasonal effect, described using the sine of Julian date for period i, combined with a categorical variable for whether i occurred in winter (Dec 21 – Mar 19), spring (Mar 20 – Jun 20), summer (Jun 21 – Sep 21), or autumn (Sep 22 – Dec 20). The Julian date attributed to each observation *ikt* was the mid-point date of the 8-day period (measured each day from noon to noon). A final fixed effect we considered was the multivariate ENSO (El Niño southern oscillation) index (MEI). Monthly MEI values were taken from the Earth System Research Laboratory website (http://www.esrl.noaa.gov/psd/enso/mei/table.html) and matched with 8-day periods. MEI is a multi-variable measure over the tropical Pacific for a coupled ocean-atmosphere phenomenon that causes global climate variability on inter-annual time scales.

Since model-selection criteria are limited for random- or mixed-effects models, we constructed models through an interactive process to identify important fixed effects. First, we noted that out of 16 HARP locations, Cuvier's beaked whale were recorded at all seven sites that were > 960 m deep, plus at one additional site that was 700m deep but on a fairly steep slope (8 deg) and close (1.66km) to the 1000-m isobath. The remaining eight sites, all < 800m deep and further (1.9 to 40.6 km) from the 1000m isobath, were never visited by Cuvier's beaked whale. Therefore, within the study area, Cuvier's beaked whale habitat appears to be cleanly demarcated by a threshold depth, and so we restricted GLMM analysis to those eight sites representing areas where Cuvier's beaked whales were likely to occur, i.e., areas > 1000m deep, or > 700m deep AND within 2km of deeper (> 1000m) water.

For these eight sites included in the GLMM analysis, we first looked at the importance of the static site-characteristics: geographic location (longitude, latitude), depth, slope, aspect, distance from 1000m and 2000m isobaths. Variables with reasonable evidence of importance ($p < 0.15$) were retained. Subsequent models additionally included seasonal variables or the ENSO/MEI variable; again, variables for which $p < 0.15$ were retained. We used $p = 0.15$ as an approximate cutoff for inclusion to error on the side of not excluding potentially useful variables, and because variables for which $p \leq 0.15$ are typically retained in fixed-effects models when using model selection criteria such as AIC.

RESULTS

Analysis of the SCB towed array data resulted in a total of 18 Cuvier's beaked whale encounters, 4 Baird's beaked whale encounters, and 3 unidentified *Mesoplodon* encounters over the 4,875 km of trackline surveyed during the survey years 2008, 2010, 2011 (Figure 2).

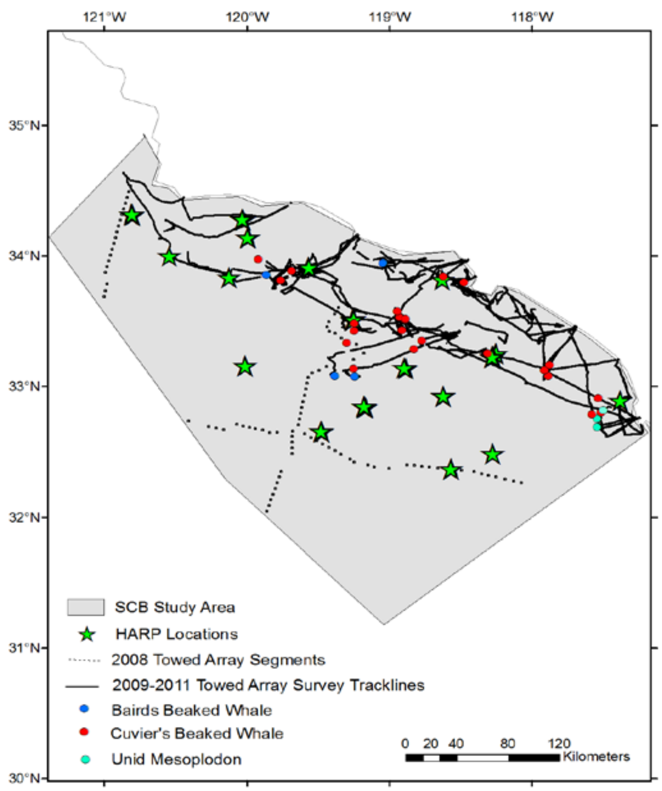

Figure 2: SCB towed array data (black tracklines) from the years 2008-2011 with detections of Baird's (blue), Cuvier's (red), and unidentified beaked whales (turquoise). Grey area denotes polygon over which habitat modeling will be performed.

The detailed analysis of SCB HARP data resulted in about 103,000 minutes (72 days) with Cuvier's beaked whale acoustic encounters. In contrast, the BW43 FM pulse, likely produced by Perrin's beaked whales (Baumann-Pickering et al. 2014), was detected over about 400 minutes (0.3 days). Cuvier's beaked whale FM pulses were predominantly detected at deeper (>1000 m), more southern, and further offshore sites (in order of relative presence: E, R, H, S, and N, to a lesser degree (<6% relative presence) G2, M, A2, minimally (<1%) P, and A; Figure 3A) within the SCB. The BW43 FM

pulse signal in comparison had higher detection rates in the more central basins of the SCB (sites A2, S, N, G2, and H, to a lesser degree (<6% relative presence) E, K3, and G, Figure 3B), indicating a possible difference in habitat preference and niche separation. It warrants further investigation to determine if this pattern of beaked whale distribution is purely based on bathymetric features or largely driven by water masses within the SCB (e.g. offshore California Current, inshore California Countercurrent, southern edge Ensenada Front) that govern a certain prey species composition and distribution.

There appears to be a seasonal pattern to the presence of Cuvier's beaked whales in the SCB at all sites (Figure 4), with generally lower probability of detection during summer and early fall months.

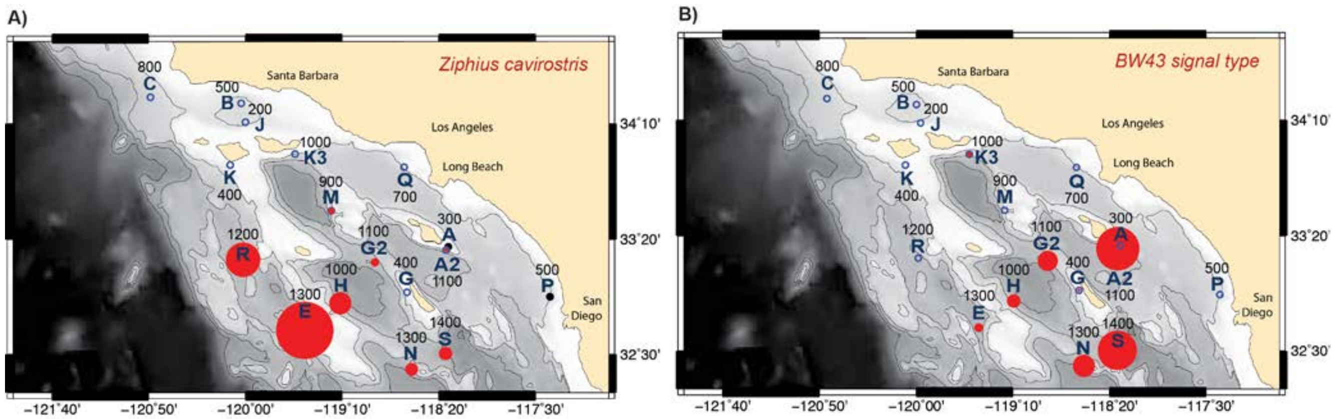

Figure 3: Relative presence (comparison of average daily encounter duration) of A) Cuvier's beaked whale and B) BW43 signal type at 18 sites in Southern California. Blue circles at sites indicate no acoustic encounters; black filled circles in A indicate <1% relative presence.

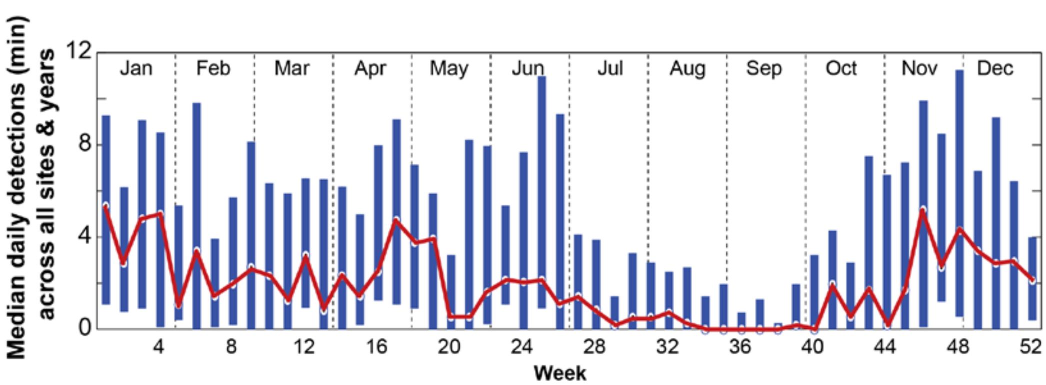

Figure 4: Median daily acoustic encounters (minutes) of Cuvier's beaked whales, across all sites with beaked whale detections and all years monitored (2006-2013) per week, indicating a seasonal presence in Southern California. Red line follows weekly medians. Blue bars are 25th to 75th percentile.

For GLMMs, DPUE$_{ikt}$ values were obtained from 995 separate 8-day periods across the 16 HARP locations and seven years (2006 – 2012). The number of 8-day periods (summed across sites) at least partially sampled in a year ranged from 21 in 2006 to 268 in 2009 (annual mean = 142).The number of 8-day periods sampled per site (summed across years) ranged from 10 to 154 (mean = 62). The number of years sampled at each location ranged from 2 to 5. The number of locations sampled in a given year ranged from 2 in 2006, to 14 in 2009 (mean = 6.7). Correcting for partial sampling of 8-day periods

and duty cycle, there were 823 complete 8-day periods (approx. 158,016 hours) of recorder sampling effort. The number of one-minute intervals during which Cuvier's beaked whales were recorded totaled approximately 1027 hours. Thus, average DPUE across the entire dataset was approximately 1.25 hours of detection per complete 8-day sampling period at a site.

For the eight HARP locations retained in the mixed-model analysis for having positive Cuvier's beaked whale detections, there were 662 $DPUE_{ikt}$ values and an average of 1.8 hours of detection per completed 8-day sampling period. $DPUE_{ikt}$ was found to vary as a function of calendar date, the MEI (ENSO) index, and spatial location. With respect to calendar date, sine(Julian day) was a highly significant variable, indicating a seasonal pattern characterized by much higher recorded Cuvier's beaked whale activity in winter and spring than in summer and autumn. The significance of the categorical term for "winter" indicated lower use in winter than in spring (Table 1, Table 2, Figure 5). The MEI index variable was also highly significant, indicating higher activity in time periods when the MEI index increased (Figure 6). However, this is difficult to interpret. Annual mean DPUE tracked annual mean MEI from 2008-2011 but not from 2006-2008, or from 2011-2012 (Figure 7), but it is difficult to gauge the true consistency of the relationship because different locations were sampled in different years. For example, the decline in mean DPUE from 2011 and 2012 is at least partially because location R, which recorded the second-highest vocalization rate overall, was sampled in 2011 and not 2012. MEI also has a seasonal pattern (higher values in summer, Figure 8), so the MEI index may also be acting as a seasonal proxy. In spite of this variable's significance, it did not seem to explain much of the total variance in the data, as residual variance was similar in models that did not include this variable.

Finally, though less conclusive based on larger p-values (> 0.10), spatial location may have been important, with significant latitude x longitude terms suggesting greater DPUE in areas further offshore. Other site-variables such as bottom depth, aspect, slope, etc., were not important for those sites already > 1000 km or close to 1000-km isobaths.
Total variance in the log-transformed dataset (i.e., for the log(DPUE+1) values) was 0.52. Residual variance from the model we have reported on was 0.23, suggesting that approximately 44% of total variance in the data were explained by the random and fixed-effects variables (variance explained is an approximation because the dataset is unbalanced). A similar measure comes from the Adjusted R^2 value from a regression of the fitted estimates vs. observed data; this value was 0.48. Estimated random effect variance was 0.06 for year and 0.03 for site, indicating that between-year variation was more important than between-site variation. Fixed-effects explained roughly 38% of the total variance in this dataset.

Overall, the fit of the final model to the data appeared reasonable in the sense that there was no significant pattern to the residuals with respect to the fixed-effect variables (Figure 9 B-D), and there is clearly a real relationship between the predictions and the observations (Figure 9A). However, negative values of log(DPUE+1) were predicted by the Gaussian model, and there were many zeros in the data resulting in non-normally distributed residuals. Moreover, the highest observed log(DPUE+1) values were systematically under-predicted. Alternative error structures, such negative binomial or gamma-Poisson, should be explored, perhaps using Bayesian methods, which would allow for greater flexibility in how random effects are modeled. However, the current analysis was sufficient for identifying which variables are qualitatively related to Cuvier's beaked whale detection rates.

Table 1. Parameter estimates for model of Cuvier's beaked whale detections. The response variable is log($DPUE_{ik}$ + 1).

	Estimate	SE	P
Intercept	-3027	1547	0.12
Latitude	88.9	46.9	0.13
Longitude	-25.7	13.0	0.12
Lat x Lon	0.76	0.40	0.13
Sine(JulianDate)	0.31	0.07	< 0.001
Summer	-0.084	0.108	0.41
Autumn	0.040	0.120	0.72
Winter	-0.127	0.058	0.02
MEI/ENSO	0.068	0.022	0.001

Table 2. Random effects, indicating mean annual and site differences between observations and the expectation from fixed-effects. For example, log(DPUE+1) was, on average, 0.39 lower in 2006 than would have been predicted for a "typical" year given other variables in the model.

Site			Year	
A2	0.11		2006	-0.39
E	0.04		2007	0.05
G2	-0.21		2008	-0.01
H	0.006		2009	0.32
M	-0.02		2010	0.13
N	-0.13		2011	-0.04
R	0.08		2012	-0.06
S	0.13			

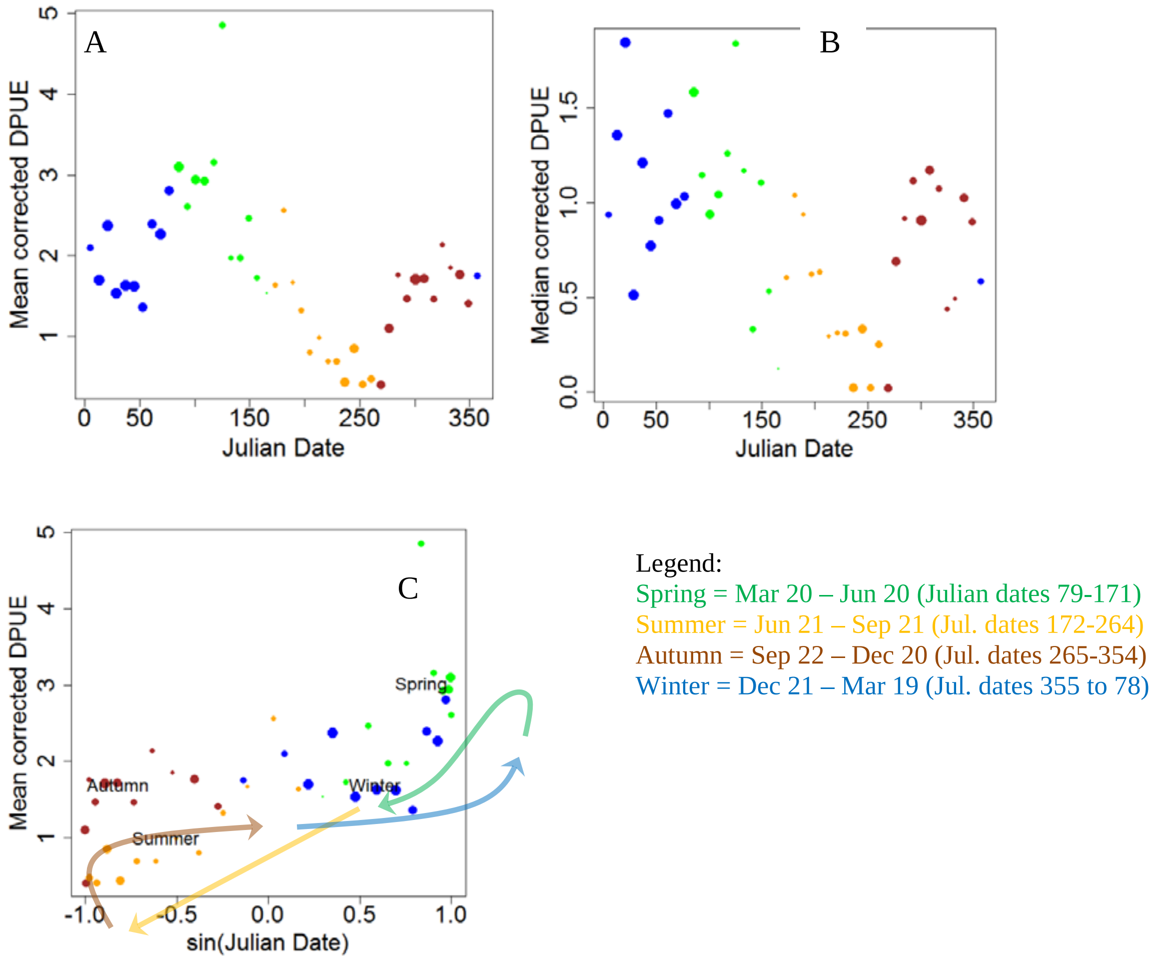

Figure 5. Plots of mean DPUE (or median DPUE, plot B) as a function of date. DPUE = number of detection hours divided by hours of effort (corrected for % time and duty cycle). Each symbol represents the mean DPUE, across all sites and years, per 8-day period within the calendar year (symbol date = midpoint of the 8-day period). Circle size reflects the number of samples per 8-day period, which ranged from 4 (Julian date = 165) to 21 (Julian dates 37 and 45). Mean number of samples per 8-day period was 14.7 (SD = 3.9). Plots A and C show the same information, but with date represented differently. Arrows in panel C are drawn by eye and are intended just to show the general qualitative pattern (are not necessarily the best-fit lines to the data).

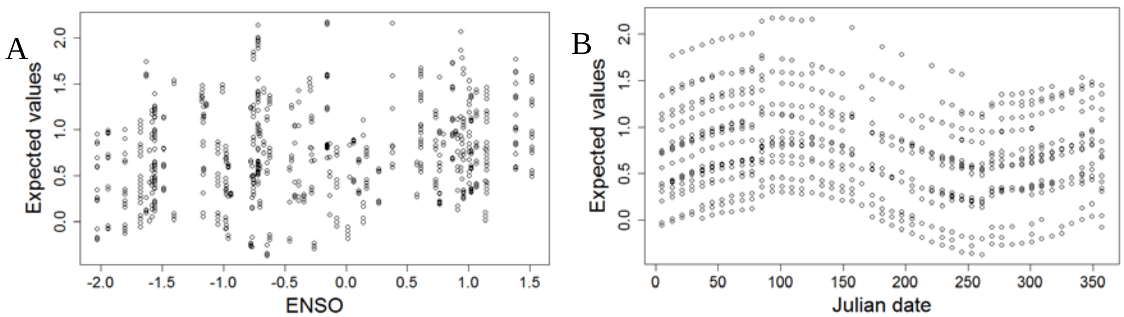

Figure 6. Expected (fitted) values of log(DPUE$_{ikt}$+1) plotted against two significant fixed-effects variables in the mixed-effects regression model: (A) MEI/ENSO, and (B) Julian date. Variation in the expected response, with respect to a given value of the predictor value, is a function of other fixed- and random-effects in the model.

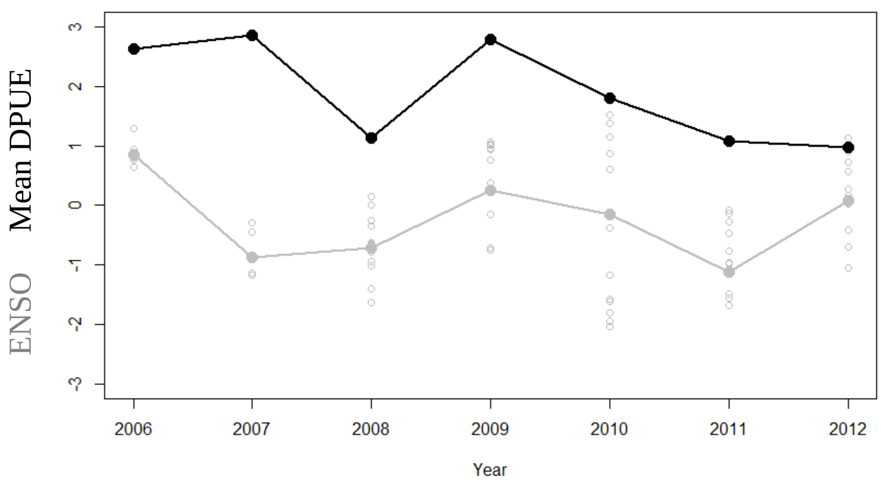

Figure 7. Simple annual means for ENSO/MEI values (gray) and DPUE, across all 8-day sampling periods and sites (no weightings applied). Open gray circles show the actual ENSO/MEI values per 8-day sampling period per site.

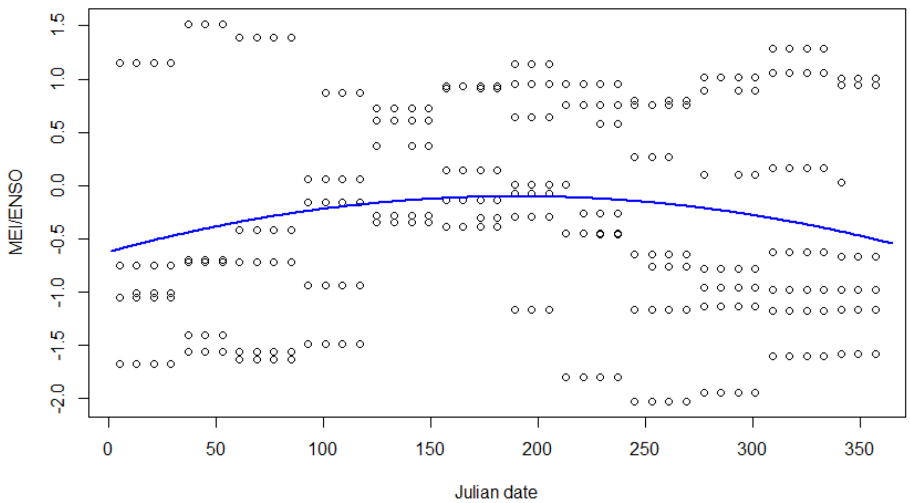

Figure 8. Relationship between Julian date and MEI index values. Each point represents the MEI index for an 8-day sampling period (midpoint date) within a year of the study. The solid line is the best least-squares regression line with first and 2nd order polynomial terms for Julian date.

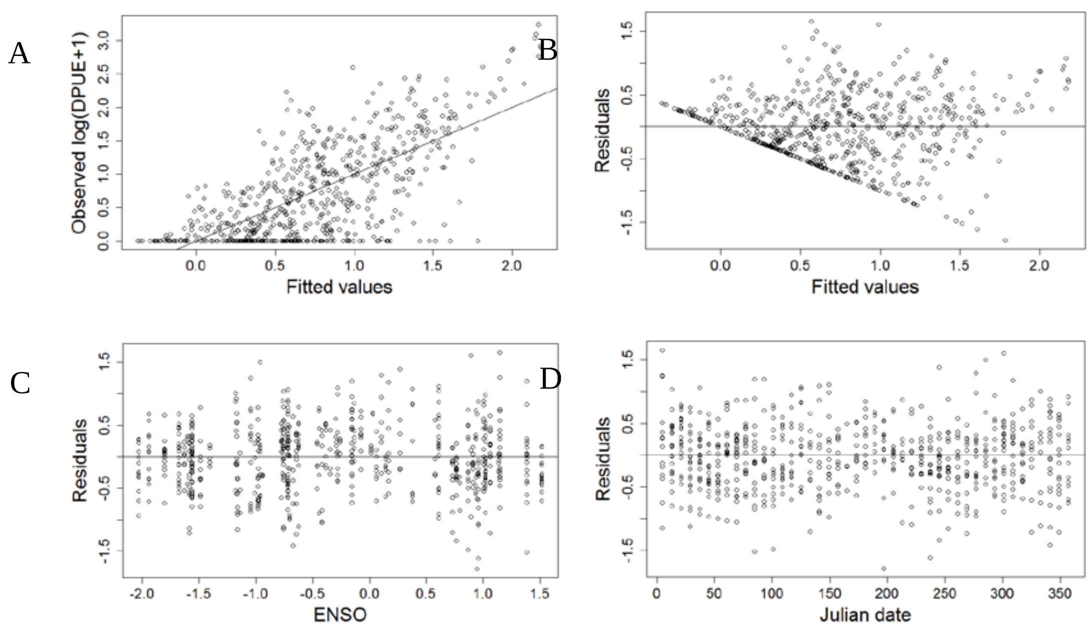

Figure 9. Diagnostic information about fit of the "best model" to the data. This model includes fixed effects (Lat, Long, Lat*Long, sin(Julian.date), categorical season variable, ENSO) and random effects (year + site). Panel A = fitted vs. observed values; B = fitted vs. residuals; C = ENSO vs. residuals; D = Julian date vs. residuals.

IMPACT/APPLICATIONS

The software tool developed to verify automated classification has proven useful for a variety of projects to date. Habitat models provide knowledge about foraging and habitat preference and potential shifts due to seasonal or oceanographic factors. This is crucial information for conservation and management as well as mitigation of potential effects of Naval activities, as well as planning for future fieldwork.

TRANSITIONS

The beaked whale FM pulse detector refined within this project is being used for US Navy Fleet range monitoring in SOCAL, NWTRC, GATMAA, MIRC, Cherry Point OPAREA, and JAX.

RELATED PROJECTS

ONR N001210904 Habitat modeling of fin and blue whales in the Southern California Bight. PI Ana Širović and John Hildebrand. The same HARP sites were used for the modeling, but investigating the low frequency range of the acoustic recordings. Efforts in propagation modeling and gathering of external oceanographic data as well as thoughts on modeling methods overlap.

NOPP N00014-11-1-0697 Acoustic Metadata Management and Transparent Access to Networked Oceanographic Data Sets. PI Marie Roch, Co-PI Simone Baumann-Pickering, John A. Hildebrand et al. A metadata management system was developed, which allows access to locally stored acoustic detections and metadata and links in a standardized way to external sources, such as oceanographic or ephemeris data. We were able to benefit from advances made under the NOPP grant in the management, retrieval, and manipulation of metadata.

PACFLT CESU W9126G-13-2-0016 Passive Acoustic Monitoring for PACFLT Naval Training Ranges. PI John Hildebrand and Co-PI Sean Wiggins. Provided support to collect and analyze acoustic data in the Southern California Range Complex.

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